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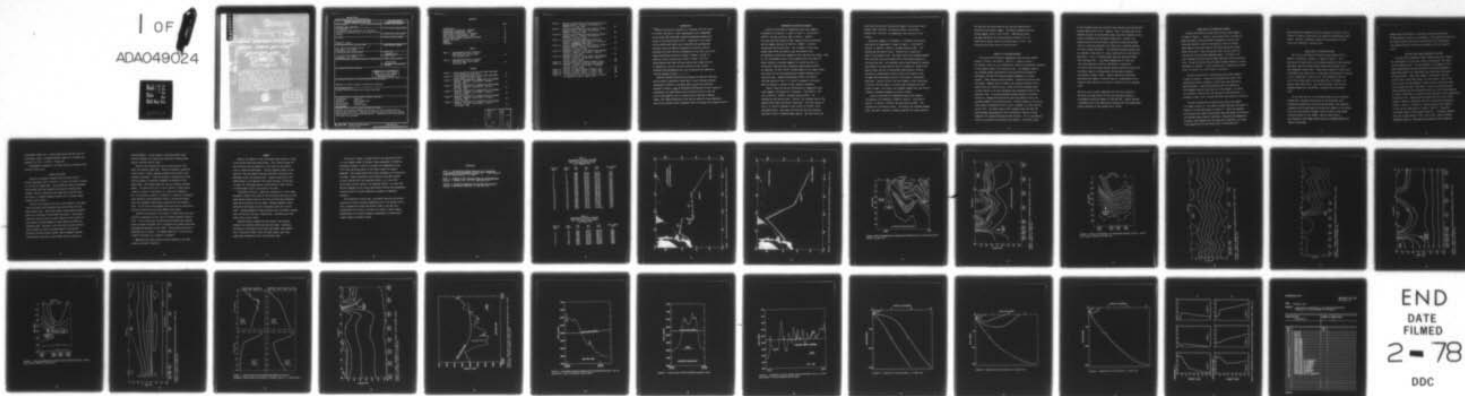
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OCEANOGRAPHIC OBSERVATIONS OF THE SUBAR
SUBTROPICAL TRANSITION ZONE IN THE
WESTERN NORTH PACIFIC.

17 SEP 1976

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This report presents the principal findings of two oceanographic/geophysical surveys conducted by the USNS SILAS BENT within the polar frontal zone of the North Pacific. Transonal temperature and sound velocity structures were determined and frontal features associated with the zone's boundaries were investigated. Three representative acoustic ray diagrams were prepared and the extent of intrusion into the deep sound channel of certain bathymetric features associated with the Hess and Shatsky Rise and the Emperor Seamount Chain were determined. The oceanographic structure southeast of Kamchatka Peninsula was found to be particularly complex.



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| REPORT DOCUMENTATION PAGE | | READ INSTRUCTIONS BEFORE COMPLETING FORM |
|---|-----------------------|--|
| 1. REPORT NUMBER Technical Note 3440-6-76 | 2. GOVT ACCESSION NO. | 3. RECIPIENT'S CATALOG NUMBER |
| 4. TITLE (and Subtitle) Oceanographic Observations of the Sub-Arctic - Subtropical Transition Zone in the Western North Pacific | | 5. TYPE OF REPORT & PERIOD COVERED |
| | | 6. PERFORMING ORG. REPORT NUMBER |
| 7. AUTHOR(s) Charles W. Senior | | 8. CONTRACT OR GRANT NUMBER(s) |
| 9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Naval Oceanographic Office Washington, D.C. 20373 | | 10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS |
| 11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Naval Oceanographic Office Washington, D.C. 20373 | | 12. REPORT DATE September 1976 |
| | | 13. NUMBER OF PAGES |
| 14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) | | 15. SECURITY CLASS. (of this report) UNCLASSIFIED |
| | | 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE |
| 16. DISTRIBUTION STATEMENT (of this Report) | | |
| <div style="border: 1px solid black; padding: 5px; text-align: center;"> DISTRIBUTION STATEMENT A Approved for public release; Distribution Unlimited </div> | | |
| 17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report) | | |
| Approved for public release; distribution unlimited. | | |
| 18. SUPPLEMENTARY NOTES Cruises 343613 and 343615 by the USNS SILAS BENT | | |
| 19. KEY WORDS (Continue on reverse side if necessary and identify by block number) | | |
| Oceanography Salinity Acoustics Water Temperature Pacific Ocean Bathymetry Sound Velocity Critical Depth Ray Diagrams | | |
| 20. ABSTRACT (Continue on reverse side if necessary and identify by block number) | | |
| Reports the principal findings of surveys in the polar frontal zone in February and April 1976. Temperature, salinity and sound velocity profiles were obtained at 28 stations using SVSTD's. Temperature and sound velocity structures are discussed. | | |

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INTRODUCTION

During the periods 6 February to 27 February 1976 and 5 April to 25 April 1976 the U.S. Naval Oceanographic Office (NAVOCEANO) survey vessel USNS SILAS BENT conducted oceanographic/geophysical surveys in the western North Pacific. Objectives of the surveys (Cruises 343613 and 343615) were to determine the oceanographic structure across the subarctic-subtropical transition zone and delineate the fronts marking the boundaries of the zone. The cruise tracks and station locations are shown in figures 1 and 2. In addition, station locations are listed in Tables 1 and 2. A Bissett-Berman model 9040 SVSTD was used to obtain depth profiles of temperature, salinity, and sound velocity at each station. Expendable bathythermographs were used to determine the temperature structure between stations.

The well-defined transition zone between the Subarctic Water Mass and the Central (subtropical) Water Mass is one of the more dominant oceanographic features of the North Pacific. From the confluence northeast of Honshu, Japan of the Oyashio and Kuroshio Currents (subarctic convergence), the zone extends across the North Pacific to near the coast of North America with an average width of 500-1000 kilometers (Roden, 1971). The boundaries of the zone are marked by large temperature and salinity gradients which profoundly affect long-range sound transmission.

TEMPERATURE DISTRIBUTION-FEBRUARY

Vertical distribution of temperature along track segment 1 (6 February to 8 February) is shown in Figure 3. From $35^{\circ}02'N.$, $140^{\circ}59'E.$ the mean course was 038° to $40^{\circ}16'N.$, $146^{\circ}07'E.$ The course was then altered to 000° , subarctic water was observed and the segment terminated at $40^{\circ}22'N.$, $146^{\circ}06'E.$ The total distance was 420 nautical miles. The isotherms of steep slope between about $35^{\circ}N.$ and $36^{\circ}20'N.$ mark the Kuroshio Front, the southern or subtropical boundary of the transition zone (Kawai, 1955). At $37^{\circ}N.$ the downward slope of the isotherms within the upper 150 meters indicates a westward component of current velocity. An anticyclonic warm-core eddy, extending to approximately $38^{\circ}30'N.$, was observed. At $39^{\circ}N.$ the $4^{\circ}C$ isotherm began to rise steeply toward the surface as the track approached the northern boundary of the transition zone. Between approximately $39^{\circ}40'N.$ and $39^{\circ}50'N.$ the tight spacing of the 3° , 4° , and $5^{\circ}C$ isotherms at 100 meters marks the Oyashio or Subarctic Front (subarctic boundary).

Figure 4 shows the vertical distribution of temperature along track segment 2 (8 February to 11 February). From $40^{\circ}34'N.$, $146^{\circ}07'E.$ to $39^{\circ}47'N.$, $159^{\circ}24'E.$ the mean course was 095° . The distance was 610 nautical miles. Station 1 was occupied north of the Oyashio Front within the Subarctic Water Mass. The tight spacing of the 3° , 4° , and $5^{\circ}C$ isotherms in the vicinity of $147^{\circ}30'E.$ marks the Oyashio Front. Once across the front and into the transition zone the 4° and $5^{\circ}C$ isotherms deepen rapidly. The track across the

transition zone possibly traversed the edges of anticyclonic eddies between 148°E. and 150°E. and between 150°30'E. and 153°20'E. Between 155°E. and 160°E. the temperature distribution was quite uniform.

Along track segment 3 (14 February - 15 February) the vertical distribution of temperature is shown in Figure 5. From 36°32'N., 159°02'E. to 32°30'N., 158°01'E. the mean course was 190°. The distance was 258 nautical miles. Station 9 was occupied just north of the Kuroshio Front. The steep slope of the isotherms between 36°N. and 35°N. marks the Kuroshio Front, the southern boundary of the transition zone. The convenient rule-of-thumb adopted by Japanese investigators, the observance of the 15°C isotherm at a depth of 200 meters, places the axis of the Kuroshio (more properly: Kuroshio Extension) at approximately 35°10'N. South of the Kuroshio Front the upper 500 to 600 meters consists of the Central (subtropical) Water Mass. South of 34°30'N. the track appears to have intersected a cyclonic cold-core eddy as a cooling trend throughout the water column is noted. The slope of the isotherms between 33°N. and 34°30'N. indicates a westward component of current velocity.

Vertical distribution of temperature along track segment 4 (16 February to 22 February) is shown in Figure 6. From 32°30'N., 158°01'E. to 33°32'N., 179°56'W. the mean course was 089°. The distance was 1,100 nautical miles. The slope of the isotherms between 159°E. and 160°E. indicates a northern component of current velocity.

This may mark the eastern edge of the cold-core eddy partially observed on the previous segment. The Emperor Seamount Chain was crossed between $171^{\circ}20'E.$ and $171^{\circ}56'E.$ Temperatures within the upper 500 meters for the section west of about $171^{\circ}E.$ are significantly greater than for the section east of $171^{\circ}E.$ Distribution within each section is quite uniform.

TEMPERATURE DISTRIBUTION-APRIL

The vertical distribution of temperature along the track between $32^{\circ}56'N.$, $173^{\circ}52'E.$ and $50^{\circ}00'N.$, $160^{\circ}24'E.$ is shown in Figure 7. The section, 1,185 n.m., was initiated just north of the subtropical boundary in the southern region of the transition zone. The downward slopes of the isotherms between approximately $33^{\circ}N.$ and $34^{\circ}30'N.$ and between approximately $36^{\circ}N.$ and $37^{\circ}N.$ indicate westward components of current velocity. These indicate warm-core eddies. Clockwise-circulating warm-core eddies, spawned from the fringe of the Kuroshio Extension are prevalent within the transition zone. North of $41^{\circ}N.$ the isotherms begin to shoal rapidly as the track approaches the northernmost extent of the transition zone. The strong horizontal thermal gradient at 50 meters, $6^{\circ}C/35$ n.m., between $42^{\circ}N.$ and $42^{\circ}30'N.$ marks the Subarctic Front, the northern boundary of the transition zone. Shoaling steeply to the surface from a depth of 400 meters at $42^{\circ}N.$, the $5^{\circ}C$ isotherm is a prime indicator of the front. The steep slopes of the isotherms within the upper 200 meters between approximately $41^{\circ}30'N.$ and $42^{\circ}30'N.$ indicate a strong component of an eastward-directed current velocity. This is the Subarctic Current, the eastward continuation of the Oyashio. The overall slope

of the isotherms across the transition zone indicates the broad eastward-flowing, North Pacific Drift. Stations 1 and 2, occupied close to the northern extremity of the transition zone, show near-isothermal surface layers of 290 meters and 165 meters respectively. Station 3 was occupied north of the front where a subsurface minimum (dicothermal layer) of 2.65°C was observed at 175 meters and a subsurface maximum of 3.28°C at about 450 meters. The subsurface maximum observed along the remainder of the track is a major characteristic of the Subarctic Water Mass. A cell of slightly warmer water was observed between 43°N . and about 46°N . Sea surface temperatures of 3.02°C and 1.64°C were observed at $46^{\circ}41'\text{N}$. and $46^{\circ}48'\text{N}$., respectively. This quite strong horizontal thermal gradient possibly coincides with the eastern edge of a northeastward flow observed by Japanese investigators (Sugiura, 1957). Sugiura reported on observations made during the summers of 1935 and 1936 of a northeastward flow of subarctic water passing the vicinity of latitude 51°N . and longitude 163°E .

Station 8, with a surface temperature of 0.87°C was occupied in the region of coldest water ($<1.0^{\circ}\text{C}$) also observed by Japanese investigators during the summers of 1935 and 1936. Sugiura reported a southward flow in this region which connected with the southwestward current (Oyashio) off the southern Kuril Islands.

SOUND VELOCITY DISTRIBUTION-FEBRUARY

Vertical distribution of sound velocity along track segment 2 is shown in Figure 8. Station 1 was occupied within the Subarctic Water Mass where a positive gradient throughout the entire water column was observed. North of the Subarctic Front the minimum sound speed is invariably found at the surface during the coldest months of the year. Upon crossing the front into the transition zone the axis of the minimum deepened rapidly. The depth of the axis increased from the surface to about 450 meters within 50 nautical miles. Across the section the axis depth increased gradually to about 600 meters at station 8. Values along the axis increased from 1,468.9 m/sec. at station 4 to 1,474.7 m/sec. at station 8.

Vertical distribution of sound velocity along track segment 3 is shown in Figure 9. Station 9 was occupied just north of the Kuroshio Front where a minimum of 1,476.2 m/sec. was observed at about 565 meters. Crossing the Kuroshio Front the isovelocity lines deepened rapidly as did the axis of the minimum. At station 10 a minimum of 1,480.3 m/sec. was observed at about 950 meters. A minimum of 1,480.7 m/sec. at about 950 meters was observed at station 12.

Vertical distribution of sound velocity along track segment 4 is shown in Figure 10. Axis depth increased from about 810 meters at station 13 to about 865 meters at station 14. Across the remainder of the section axis depth varied between about 830 meters and 930 meters with minimum values close to 1,480 m/sec. Reflecting the temperature structure, sound speeds within the upper 400 to 500 meters are higher in the western half of the section than in the eastern half.

Sound velocity and temperature profiles obtained at stations 1 and 20 (Figure 11) typify, respectively, the subarctic and subtropical water masses. Profiles intermediate between the two extremes are found within the intervening transition zone.

SOUND VELOCITY DISTRIBUTION-APRIL

The vertical distribution of sound velocity between $40^{\circ}03'N.$, $168^{\circ}20'E.$ and $50^{\circ}00'N.$, $160^{\circ}24'E.$ is shown in Figure 12. The section was initiated close to the northern extremity of the transition zone where a positive sound velocity gradient was observed in the near-isothermal surface layer. Sound velocity maxima of 1,492.0 m/sec. at 290 meters and 1,490.8 m/sec. at 165 meters were observed at stations 1 and 2, respectively. North of $41^{\circ}N.$ the isovelocity lines and axis of the minimum, which lies just below the $5^{\circ}C$ isotherm, rise steeply toward the surface. The strong horizontal sound velocity gradient between $42^{\circ}N.$ and $42^{\circ}30'N.$ coincides with the Subarctic Front.

At the front the axis of the minimum merges with the subsurface minimum which coincides with the core of the dicothermal layer. Progressing northward from the front the dicothermal layer gradually disappears and the sound velocity minimum value appears at the surface. With a positive gradient throughout the entire water column upward refraction prevails at all depths. North of about $42^{\circ}20'N.$ the isovelocity lines deepen rapidly and curve northward beneath the Subarctic Water Mass.

Between $46^{\circ}41'N$ and $46^{\circ}45'N$. a horizontal sound velocity gradient of approximately 1 m/sec/n.m. was observed. This gradient coincides with the thermal gradient previously discussed and closely approximates the maximum horizontal sound velocity gradient across the Subarctic Front.

CRITICAL DEPTH ACROSS BATHYMETRIC SECTIONS

The most shallow bathymetric depth recorded along track segment 2 was 4,200 meters at a point just north of the Subarctic Front where critical depth was zero. For the remainder of the segment critical depth ranged between 700 and 2,000 meters with minimum bathymetric depth being greater than 5,000 meters thus presenting no blockage of the sound channel. Along track segment 3 the Kuroshio Front was found to have a significant effect on critical depth. North of the front the most shallow bathymetric depth was about 3,100 meters where critical depth was about 3,000 meters. Across the strong horizontal thermal gradient marking the Kuroshio Front the critical depth deepened to almost 3,700 meters, an increase of about 700 meters within approximately 50 nautical miles. Approaching the Shatsky Rise the critical depth shoaled slightly to 3,600 meters and first intersected the bottom at $33^{\circ}36'N$., $158^{\circ}14'E$., (Figure 13). The most shallow point observed on the rise was 2,040 meters at $32^{\circ}29'N$., $158^{\circ}11'E$. - more than 1,500 meters above critical depth (Figure 14). The Emperor Seamount Chain was crossed between $171^{\circ}22'E$. and $171^{\circ}56'E$. where a minimum bathymetric depth of 1,800 meters was observed; critical depth was

3,300 meters (Figure 15). Critical depth across the Hess Rise was 3,350 meters, where a minimum bathymetric depth of 1,710 meters was observed at $33^{\circ}17'N.$, $175^{\circ}48'E.$ (Figure 16).

No bathymetric blockage of the sound channel was observed along the April Cruise track.

ACOUSTIC RAY PATHS

Acoustic ray diagrams, prepared from the sound velocity profiles obtained at April stations 2, 3, and 8, are shown in figures 17, 18, and 19, respectively. Source depth was taken as 100 meters and ray paths which best exemplify the acoustic structure were plotted. Rays are labeled with the angles they initially leave the source; (-) denotes downward directed and (+) denotes upward directed initial angles.

Station 2 was occupied just south of the Subarctic Front where a positive sound velocity gradient was observed within the 165-meter surface layer. Below layer depth a strong negative gradient prevails to the depth of the minimum (610 meters). The diagram shows that rays with even very small negative initial angles are very quickly refracted downward to great depths and attain considerable range. Conversely, rays with even very small positive initial angles are quickly refracted upward to the surface. Reflection from the surface converts them to downward directed rays and after returning to source depth they are strongly re-

fracted downward. In this region of strong horizontal sound velocity gradients ray tracing over significant distances would require a multiple-profile input.

Station 3 was occupied just north of the Subarctic Front within the Subarctic Water Mass. Below the 100-meter isovelocity surface layer a slightly negative gradient prevails down to the minimum at 160 meters. Below the minimum a strong positive sound velocity gradient is observed throughout the remainder of the water column. The diagram shows that rays are strongly refracted upward. In contrast with the -5° ray at station 2, which attains a depth in excess of 1,500 meters at a range of 10 kilometers, the -5° ray attains a depth of 375 meters at a range of 6 kilometers. There should be strong propagation within a surface half-channel until (for southward directed rays) encounter with the Subarctic Front. At the front strong downward refraction would be experienced and direct coupling with the deep (SOFAR) sound channel.

Station 8 was occupied in the region of coldest water the origin of which is apparently off the coast of southern Kamchatka (Sugiura, 1957). A very strong positive sound velocity gradient was observed within the upper 175 meters with a strong positive gradient continuing throughout the remainder of the column. Strong upward refraction is experienced at all depths. The diagram shows the -5° ray attaining a depth of 145 meters at a range of 1 kilometer.

Temperature and sound velocity profiles obtained at the three stations are shown in Figure 20.

SUMMARY

North of the Subarctic Front the minimum sound velocity is found at the surface during the winter months. This surface minimum connects directly with the SOFAR axis, which south of the Kuroshio Front is found below 900 meters. The axis descends steeply at the Subarctic Front and deepens from about 600 meters to greater than 900 meters across the Kuroshio Front. Acoustic coupling with the SOFAR channel at the Subarctic Front should provide, in principle, at least, for long-range acoustic surveillance by a deep receiver of shallow-depth sources lying north of the front.

The Kuroshio Front has a significant influence on critical depth. Bathymetric features just north of the front may be below the critical depth whereas features south of the front with the same bathymetric depth may be above the critical depth. Minimum bathymetric depth observed on the Shatsky Rise was 1,500 meters above the critical depth. Minimum bathymetric depths observed across the Emperor Seamount Chain and the Hess Rise were, respectively, 1,420 meters and 1,640 meters above critical depth.

Mesoscale eddies, spawned from the fringe of the Kuroshio Extension are prevalent within the transition zone. Possessing attributes of the Kuroshio Front along their edges, they probably have a significant effect, within the upper layers, upon long-range sound transmission across the transition zone.

The area of, roughly, latitude 48-55°N. and longitude 153-168°E. is a very complex region of periodic large oceanographic variability. According to Sugiura, a mass of cold water with temperatures below 0.7°C forms during the winter in the coastal water off southern Kamchatka. This coldest water moves slowly southward as an anticyclonic cold eddy. Sugiura reported on an anticyclonic cold eddy centered at about latitude 52°N. and longitude 159°30'E. on 14 July 1935 and at about latitude 50°30'N. and longitude 159°30'E. on 6 Sept 1935. Periodic spawning of cold lenses significantly affects the oceanographic structure within the region immediately southeast of Kamchatka Peninsula.

With formation of anticyclonic cold eddies there must be periodic reversals of current direction immediately east of the northern Kurils. With a southward flow along the eastern fringe of the eddy and a northeastward flow further to the east the region is indeed complex. Determination of the spatial-temporal oceanographic structure would require intensive seasonal surveys.

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Roden, G., Aspects of the Transition Zone in the Northeastern Pacific, J. Geophys. Res., 76 (15), 3462-3475, 1971.

Sugiura, J. On the Sea Conditions to the East Off the Kuril Islands, Oceanographic Magazine, 10, 169-178, 1957.

TABLE 1
OCEANOGRAPHIC STATION LOCATIONS
USNS SILAS BENT CRUISE 343613
6-27 FEBRUARY 1976

| Station (No.) | Date (Feb.) | Time (Z) | Lat. (N.) | Long. (E.) | Sonic Depth (M.) |
|------------------|----------------|-------------|--------------|---------------|---------------------|
| 1 | 8 | 1058 | 40°34' | 146°07' | 5180 |
| 2 | 8 | 1806 | 40°33' | 147°06' | 5365 |
| 3 | 8 | 2359 | 40°31' | 147°47' | 5312 |
| 4 | 9 | 0804 | 40°26' | 149°06' | 5317 |
| 5 | 9 | 2122 | 40°14' | 151°36' | 5532 |
| 6 | 10 | 1405 | 40°05' | 154°13' | 5616 |
| 7 | 11 | 0351 | 39°58' | 156°48' | 5586 |
| 8 | 11 | 1838 | 39°46' | 159°24' | 5538 |
| 9 | 14 | 1003 | 36°20' | 158°56' | 3551 |
| 10 | 15 | 0014 | 34°47' | 158°36' | 4500 |
| 11 | 15 | 0935 | 33°58' | 158°19' | 4229 |
| 12 | 15 | 1924 | 33°03' | 158°08' | 3310 |
| 13 | 16 | 0746 | 32°31' | 158°59' | 2730 |
| 14 | 16 | 1637 | 32°37' | 160°00' | 4612 |
| 15 | 17 | 0224 | 32°37' | 161°16' | 5658 |
| 16 | 18 | 0259 | 32°49' | 164°59' | 6273 |
| 17 | 19 | 0840 | 33°01' | 170°02' | 5740 |
| 18 | 20 | 0651 | 33°13' | 173°28' | 5101 |
| 19 | 21 | 0936 | 33°25' | 177°24' | 3383 |
| 20 | 22 | 0516 | 33°32' | 179°56'W. | 3761 |

TABLE 2
OCEANOGRAPHIC STATION LOCATIONS
USNS SILAS BENT CRUISE 343615
5-25 APRIL 1976

| Station (No.) | Date (Apr.) | Time (Z) | Lat. (N.) | Long. (E.) | Sonic Depth (M.) |
|------------------|----------------|-------------|--------------|---------------|---------------------|
| 1 | 15 | 1850 | 40°03' | 168°20' | 5881 |
| 2 | 16 | 0945 | 41°27' | 167°17' | 5628 |
| 3 | 16 | 2302 | 42°58' | 166°12' | 4850 |
| 4 | 17 | 1152 | 44°33' | 165°11' | 5961 |
| 5 | 17 | 2156 | 45°50' | 164°07' | 5729 |
| 6 | 18 | 0905 | 47°11' | 162°52' | 5870 |
| 7 | 18 | 2015 | 48°30' | 161°46' | 5860 |
| 8 | 19 | 0810 | 50°00' | 160°24' | 5593 |

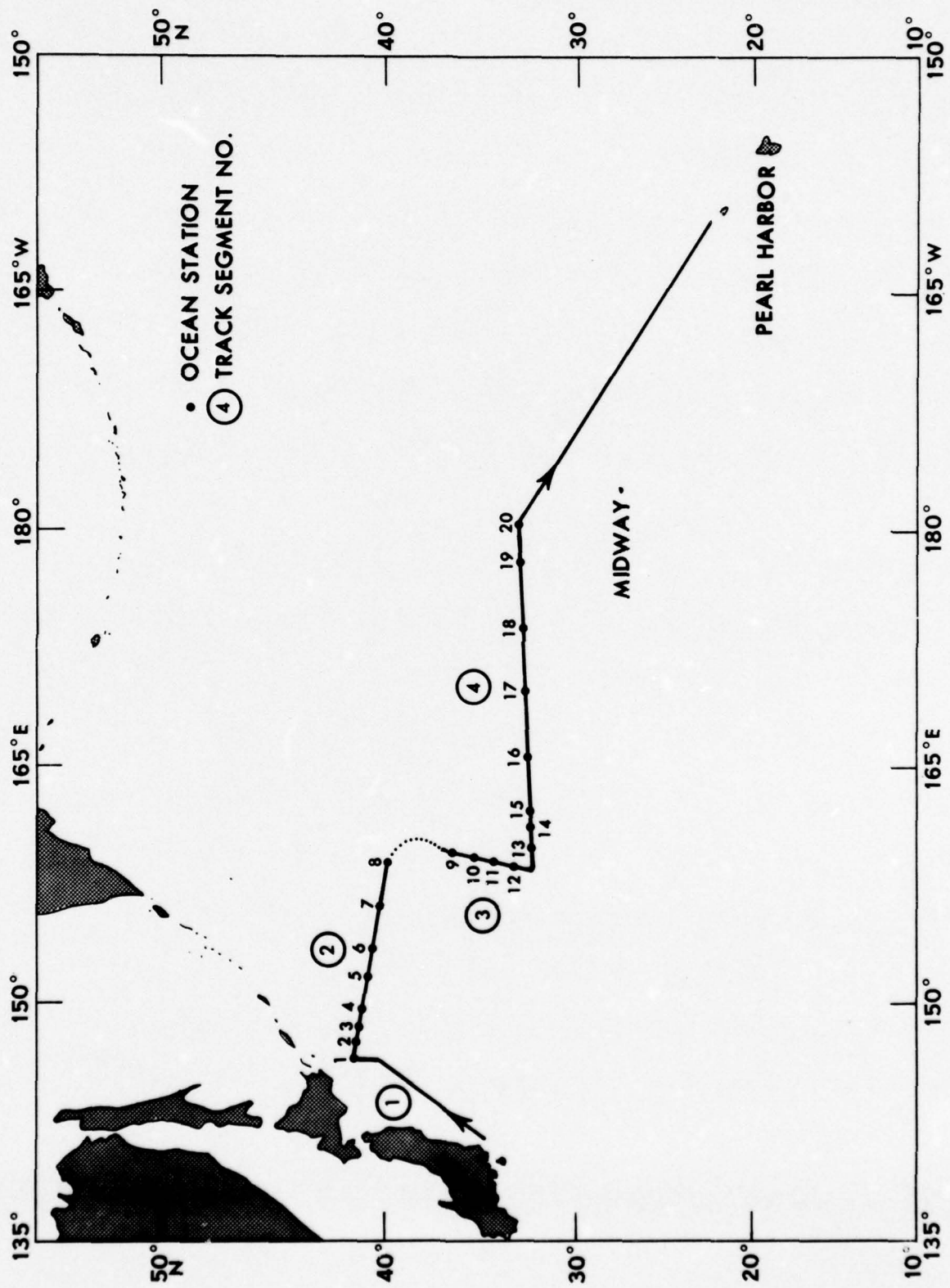


FIGURE 1 TRACK AND STATION LOCATION CHART USNS SILAS BENT CRUISE 343613 6-27 FEB. 1976

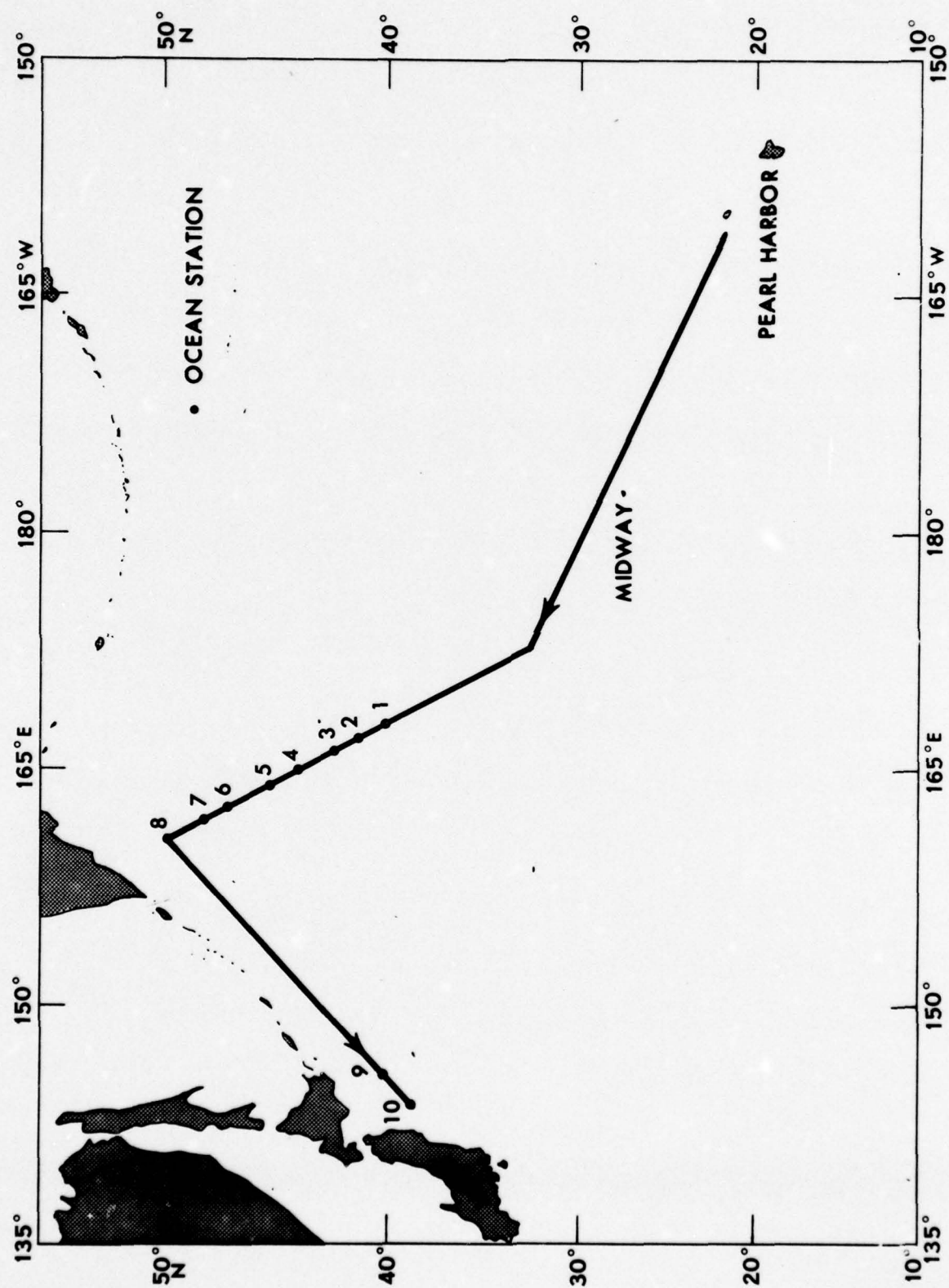


FIGURE 2 TRACK AND STATION LOCATION CHART USNS SILAS BENT CRUISE 343615 5-25 APRIL 1976

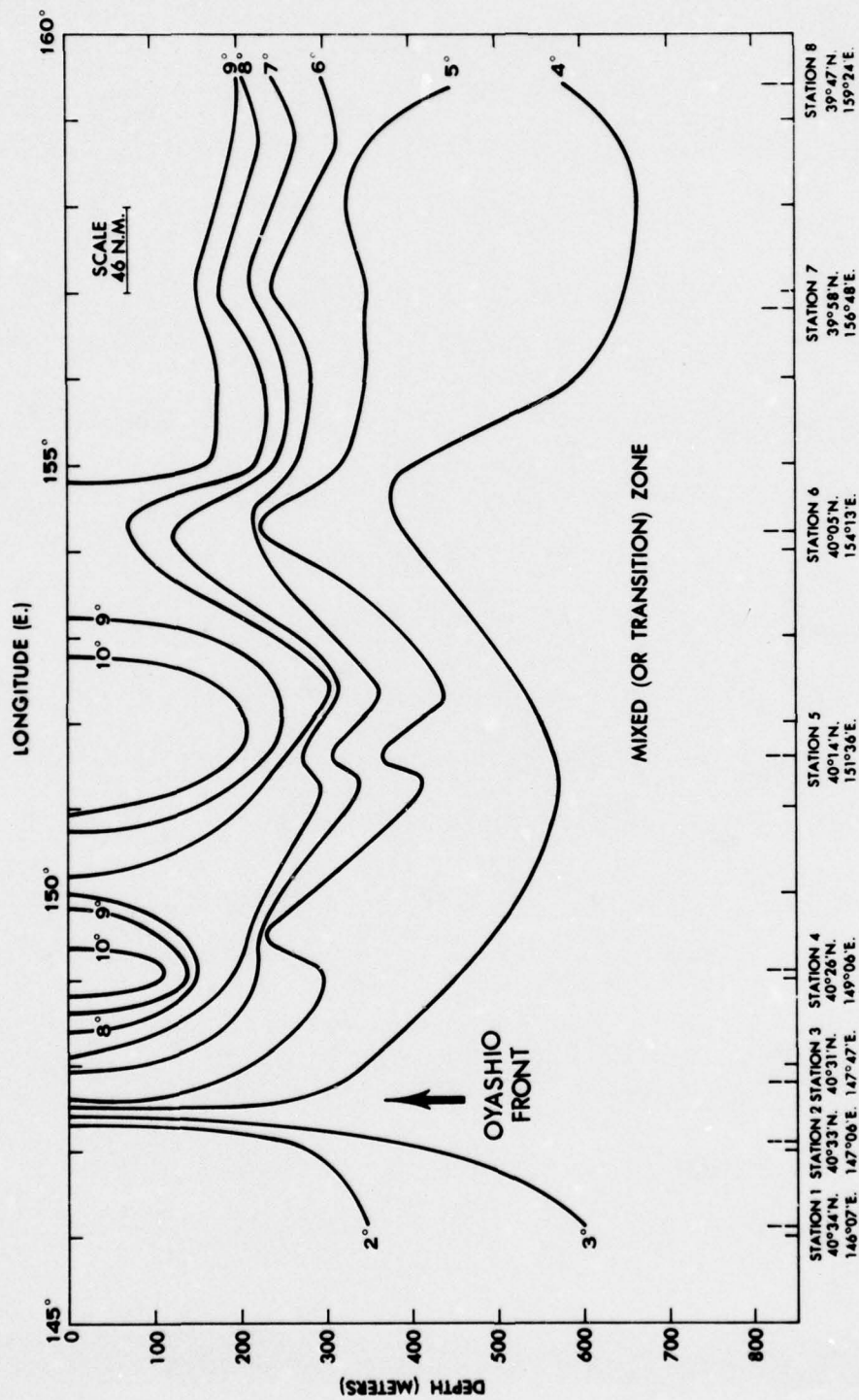


FIGURE 4 VERTICAL DISTRIBUTION OF TEMPERATURE BETWEEN 40°34'N, 146°07'E. AND 39°47'N, 159°24'E. 8-11 FEB. 1976

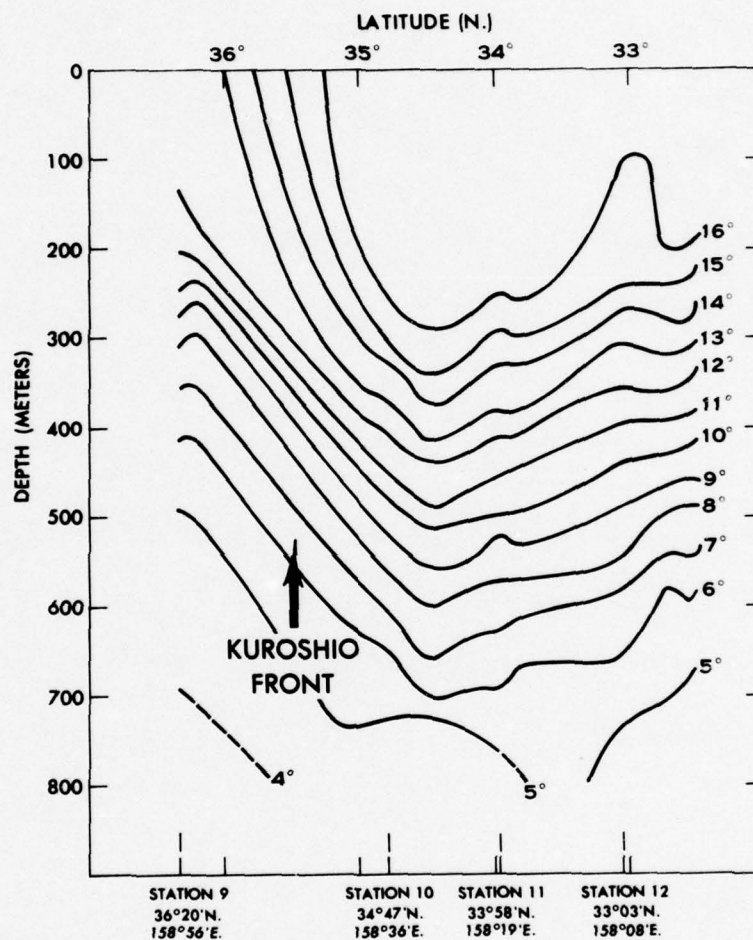


FIGURE 5 VERTICAL DISTRIBUTION OF TEMPERATURE BETWEEN 36°20'N., 158°56'E. AND 32°30'N., 158°01'E 14-15 FEB. 1976

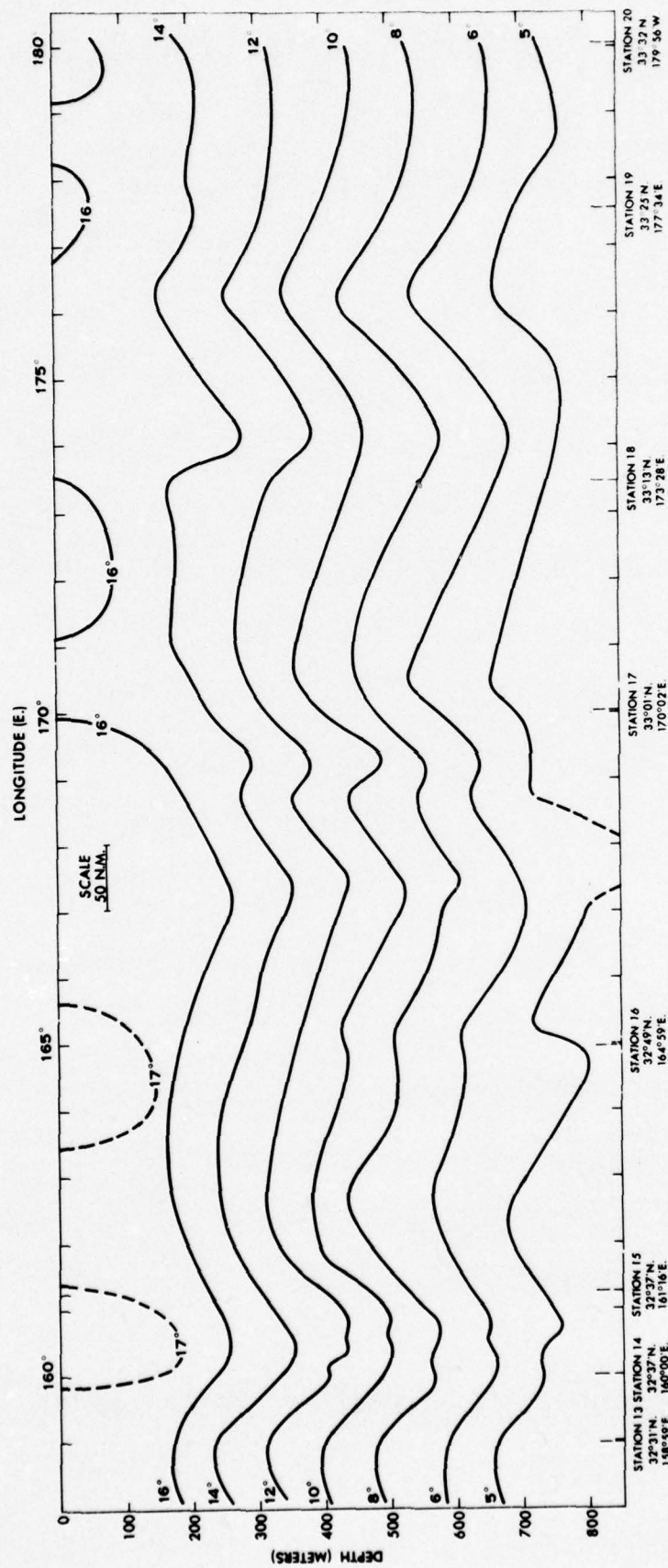


FIGURE 6 VERTICAL DISTRIBUTION OF TEMPERATURE BETWEEN 32°30'N., 158°01'E. AND 33°32'N. 179°56'E 16-22 FEB. 1976

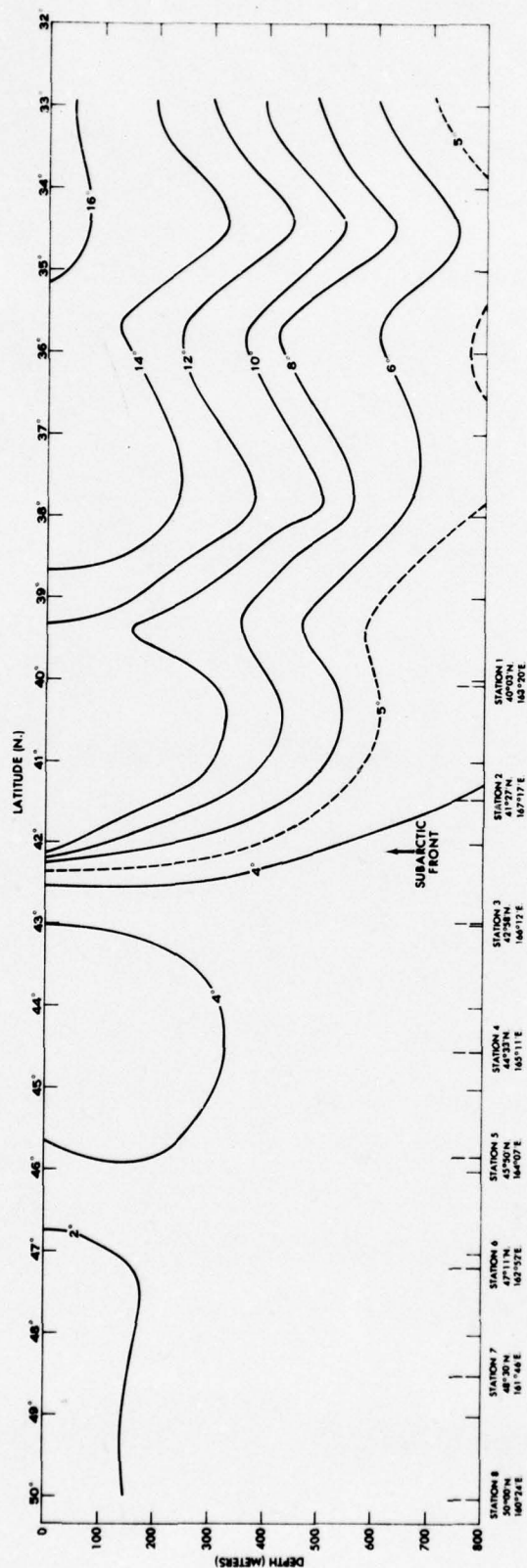


FIGURE 7 VERTICAL DISTRIBUTION OF TEMPERATURE (°C) BETWEEN 32°56'N., 173°52'E AND 50°00'N., 160°24'E 13-19 APRIL 1976.

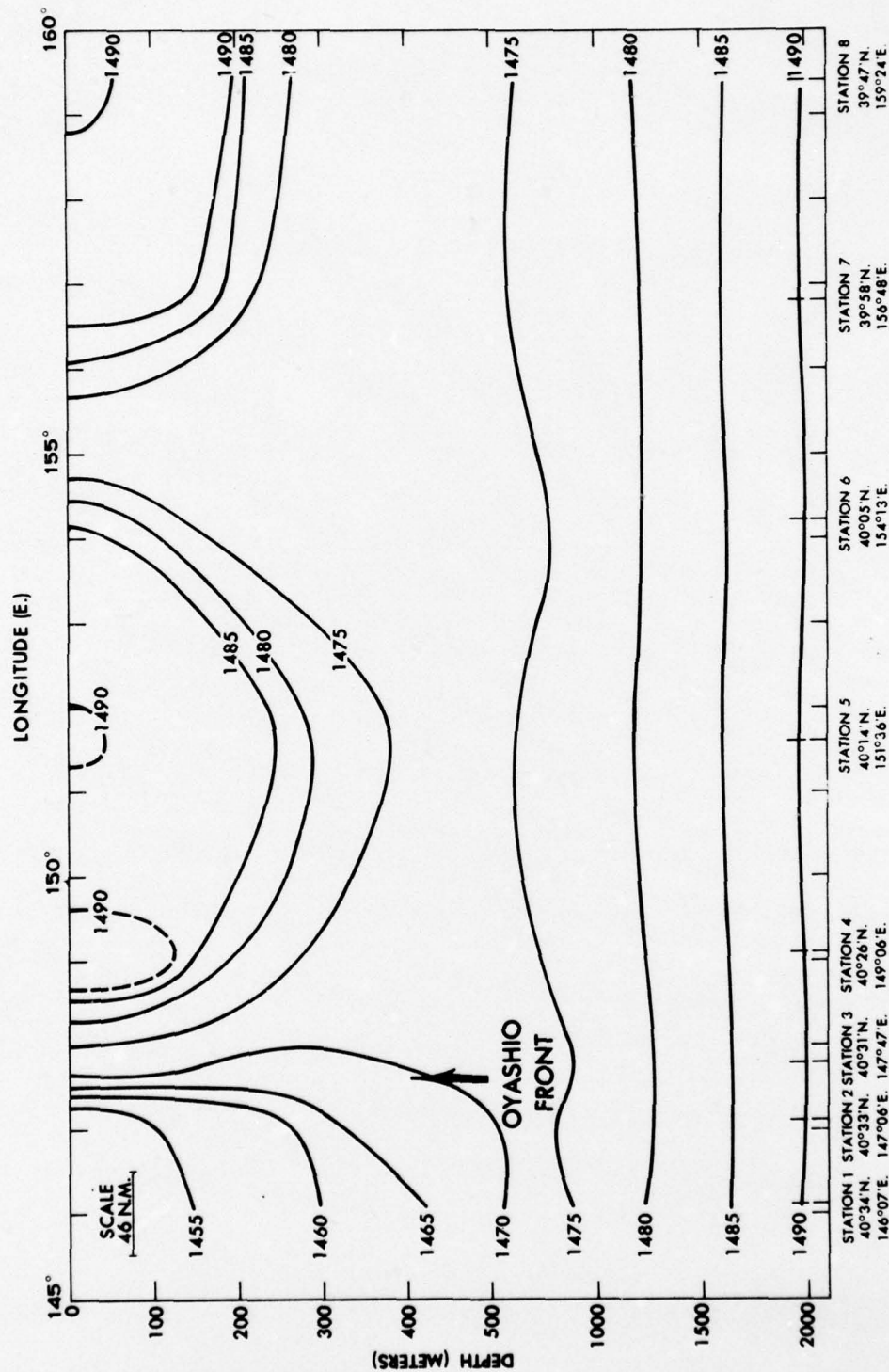


FIGURE 8 VERTICAL DISTRIBUTION OF SOUND VELOCITY BETWEEN 40°34'N., 146°07'E. AND 39°47'N., 159°24'E. 8-11 FEB. 1976

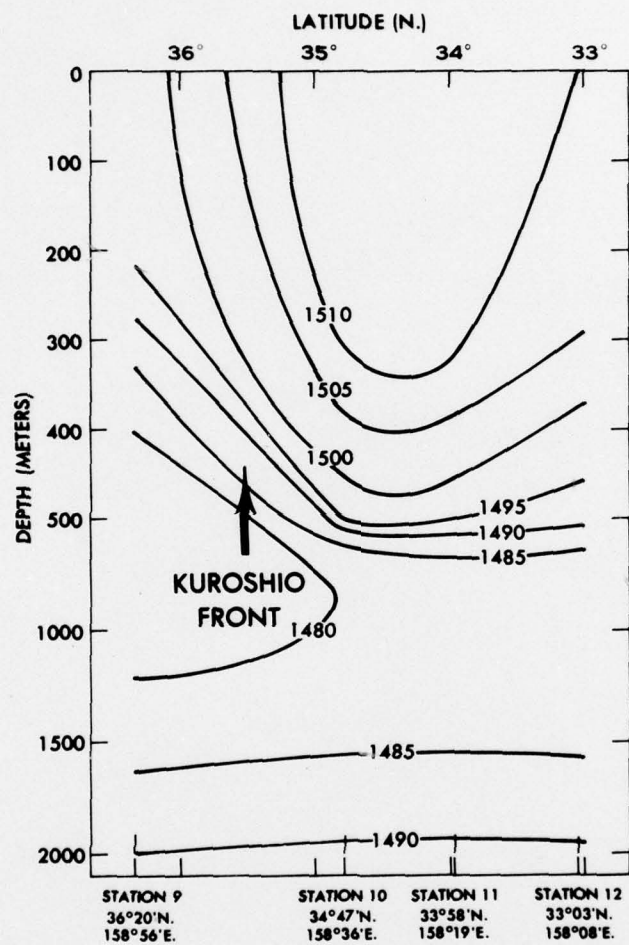


FIGURE 9 VERTICAL DISTRIBUTION OF SOUND VELOCITY BETWEEN 36°20'N., 158°56'E AND 33°03'N., 158°08'E 14-15 FEB 1976

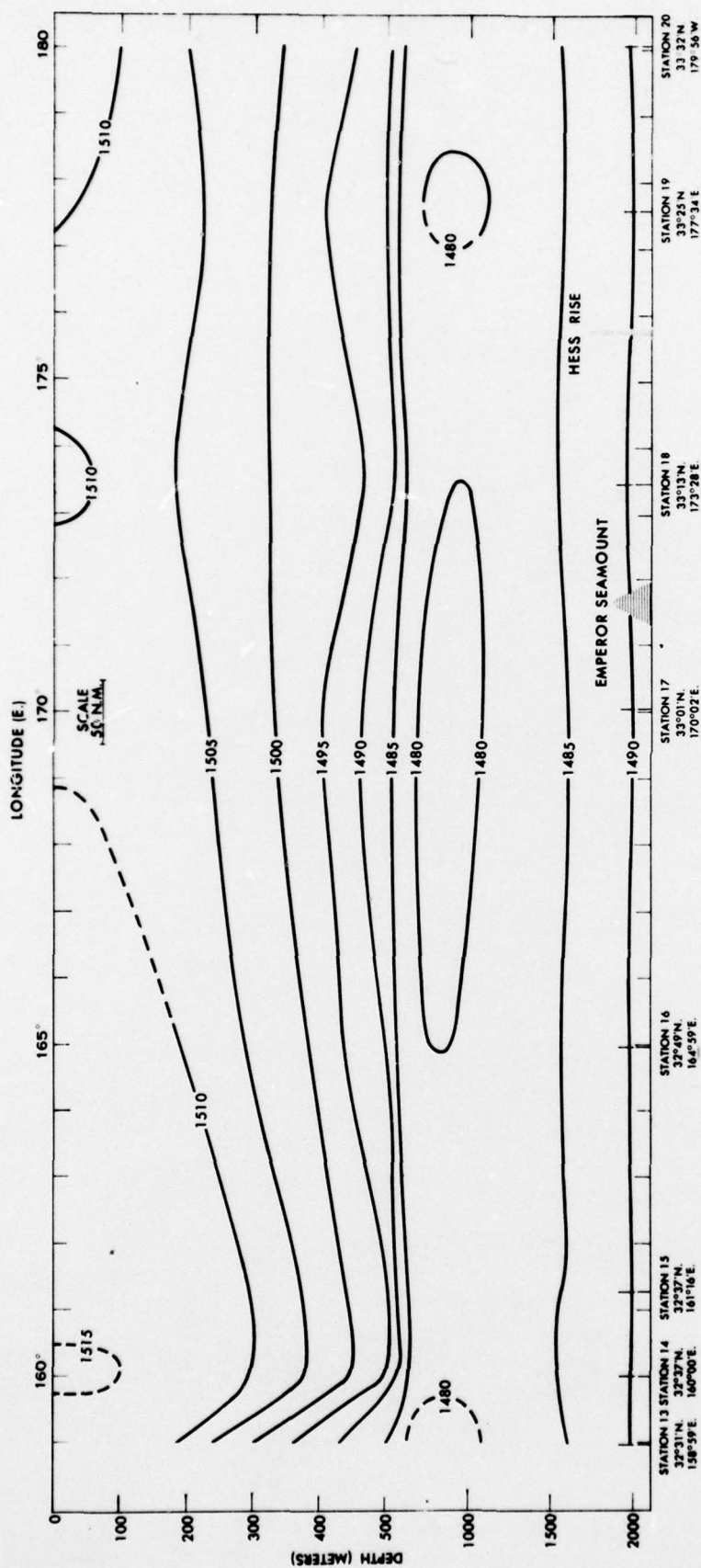


FIGURE 10 VERTICAL DISTRIBUTION OF SOUND VELOCITY BETWEEN 32°31'N., 158°59'E. AND 33°32'N., 179°56'W. 16-22 FEB 1976

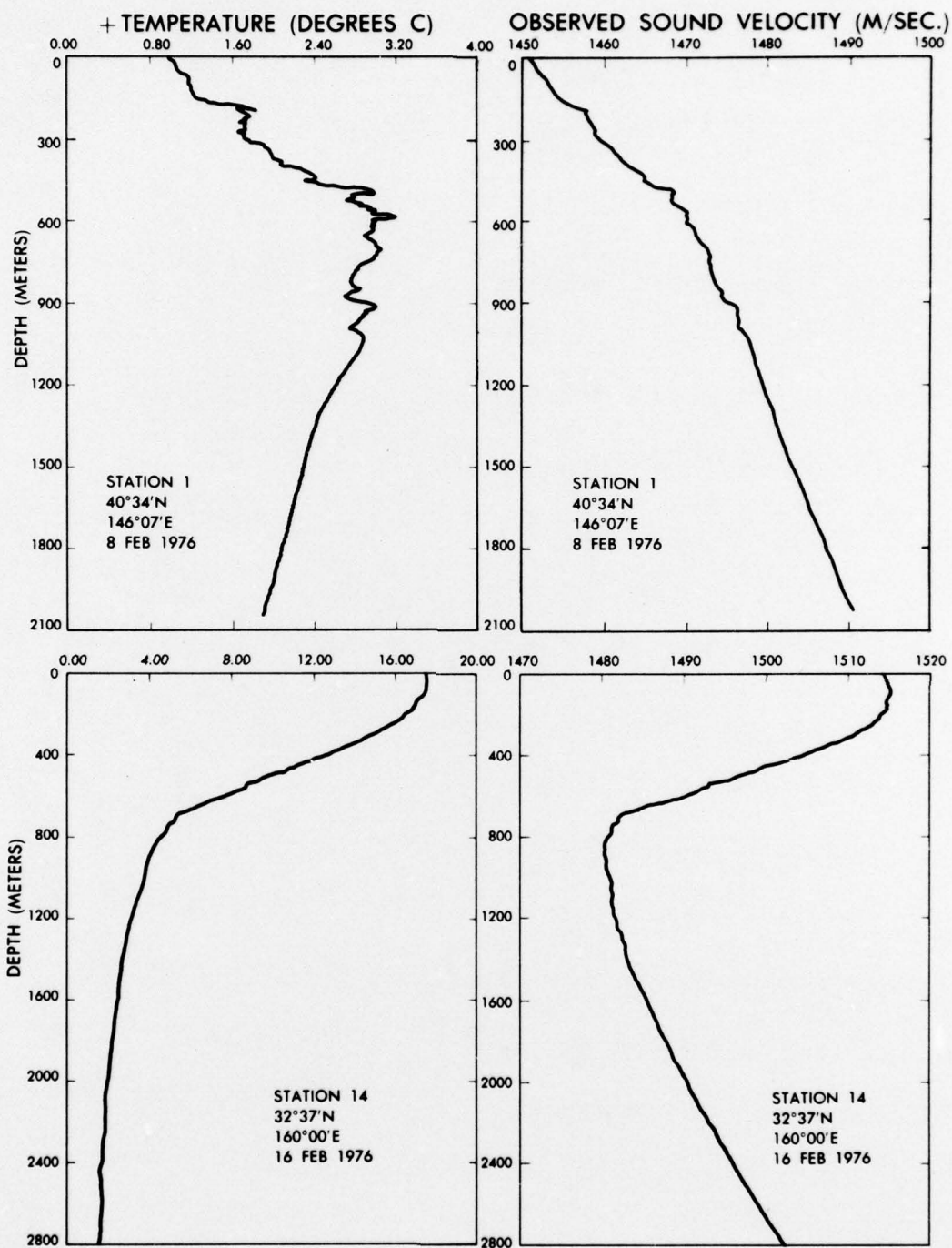


FIGURE 11 SOUND VELOCITY AND TEMPERATURE PROFILES AT STATION 1 (SUBARCTIC WATER MASS) AND STATION 14 (CENTRAL subtropical WATER MASS).

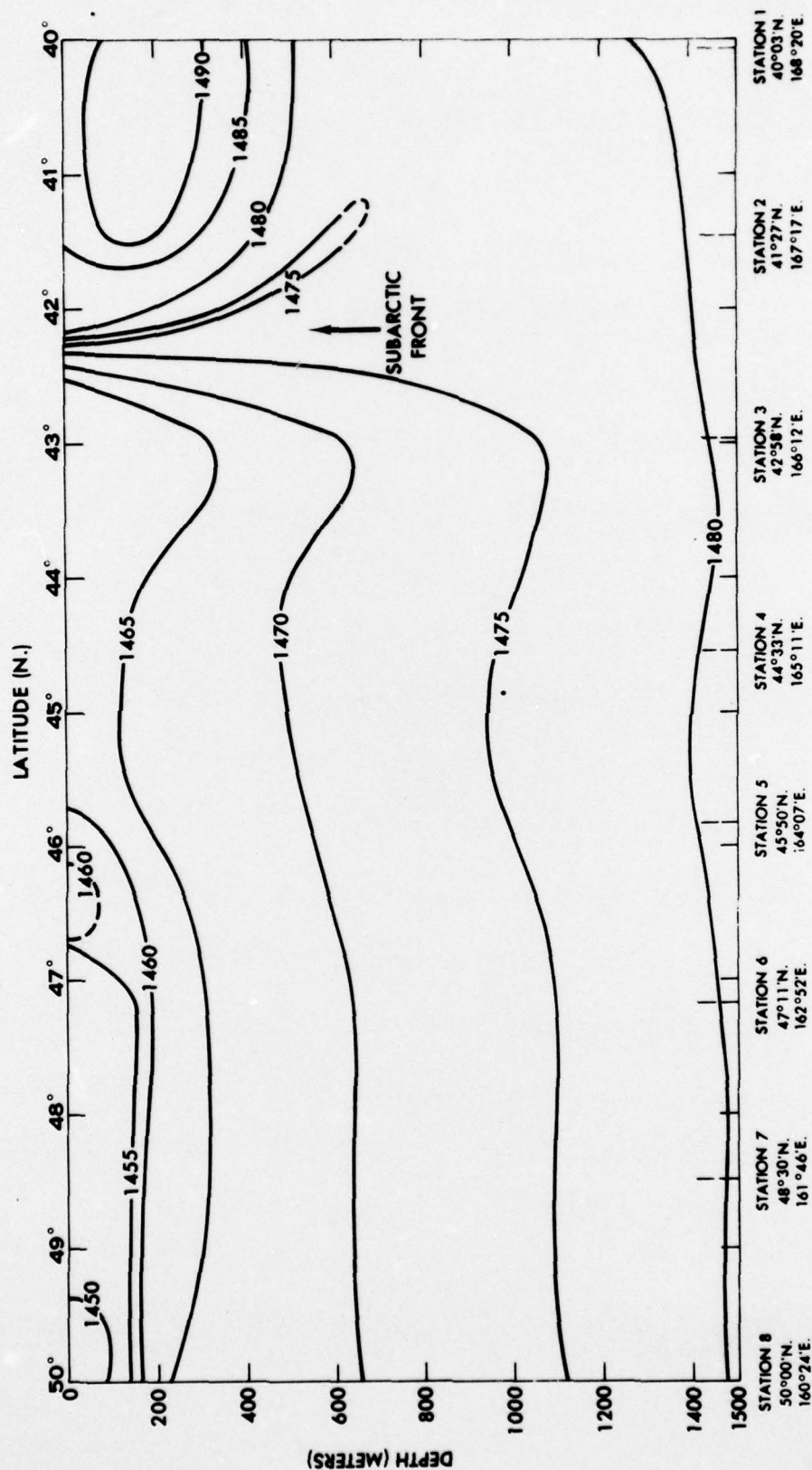


FIGURE 12 VERTICAL DISTRIBUTION OF SOUND VELOCITY (M/SEC) BETWEEN 40°03'N., 168°20'E. AND 50°00'N., 160°24'E. 15-19 APRIL 1976.

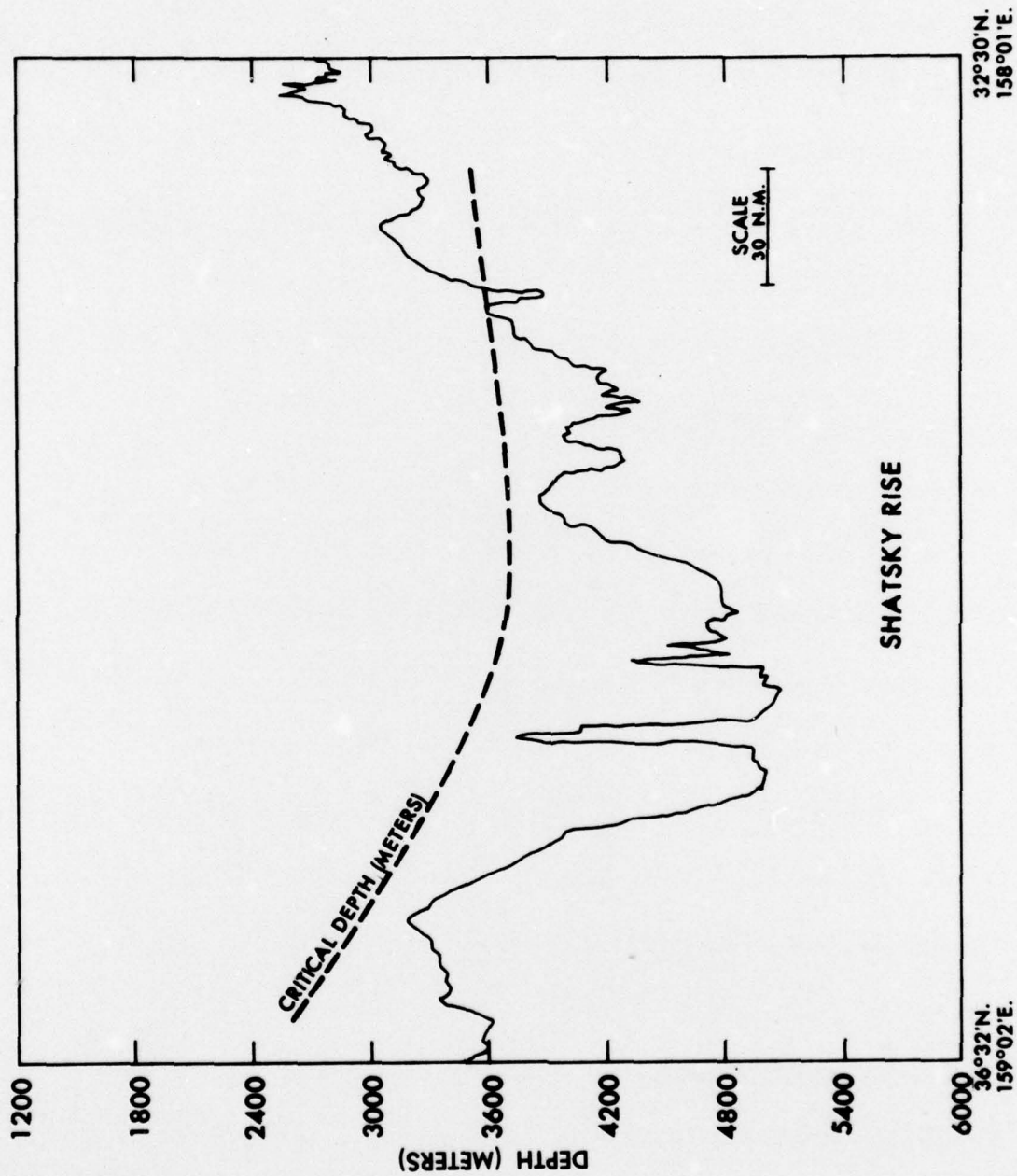


FIGURE 13 BATHYMETRIC SECTION ACROSS SHATSKY RISE BETWEEN 36°32'N., 159°02'E. AND 32°30'N., 158°01'E. SHOWING CRITICAL DEPTH.

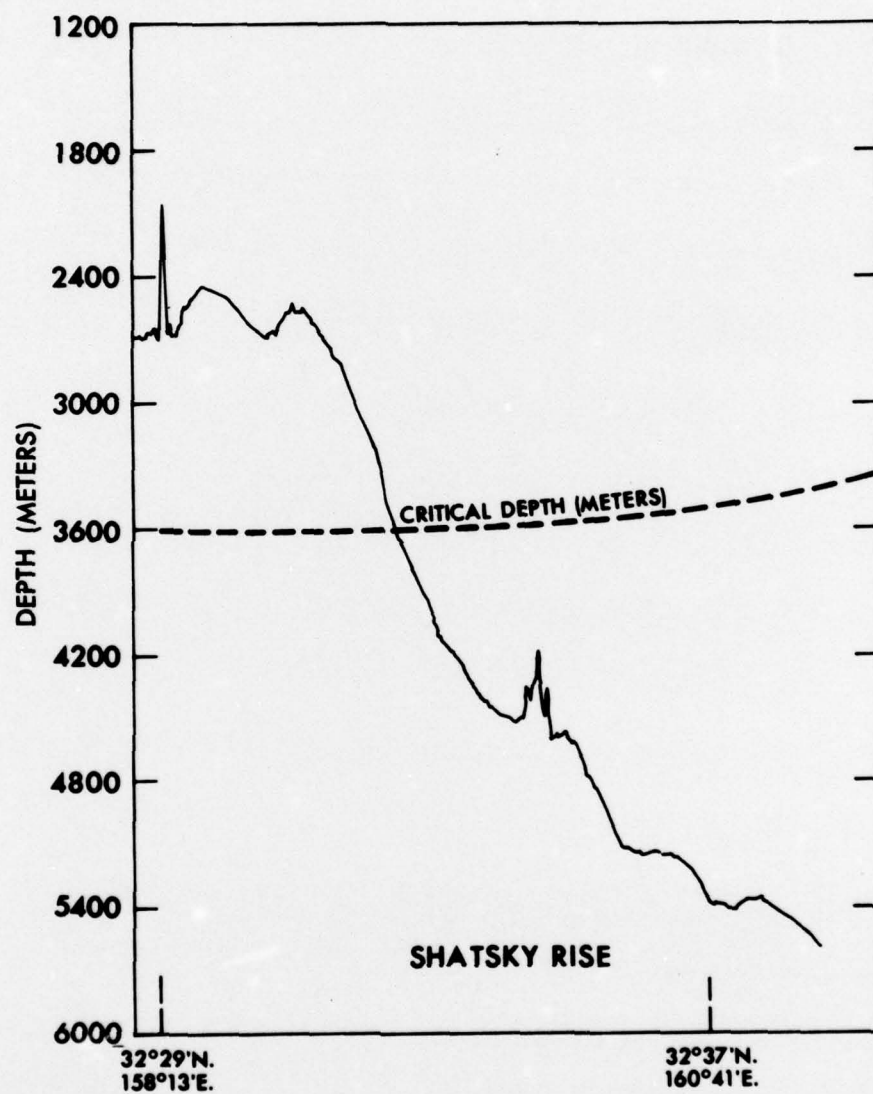


FIGURE 14 BATHYMETRIC SECTION ACROSS SHATSKY RISE BETWEEN 32°29'N., 158°13'E AND 32°37'N., 160°41'E. SHOWING CRITICAL DEPTH.

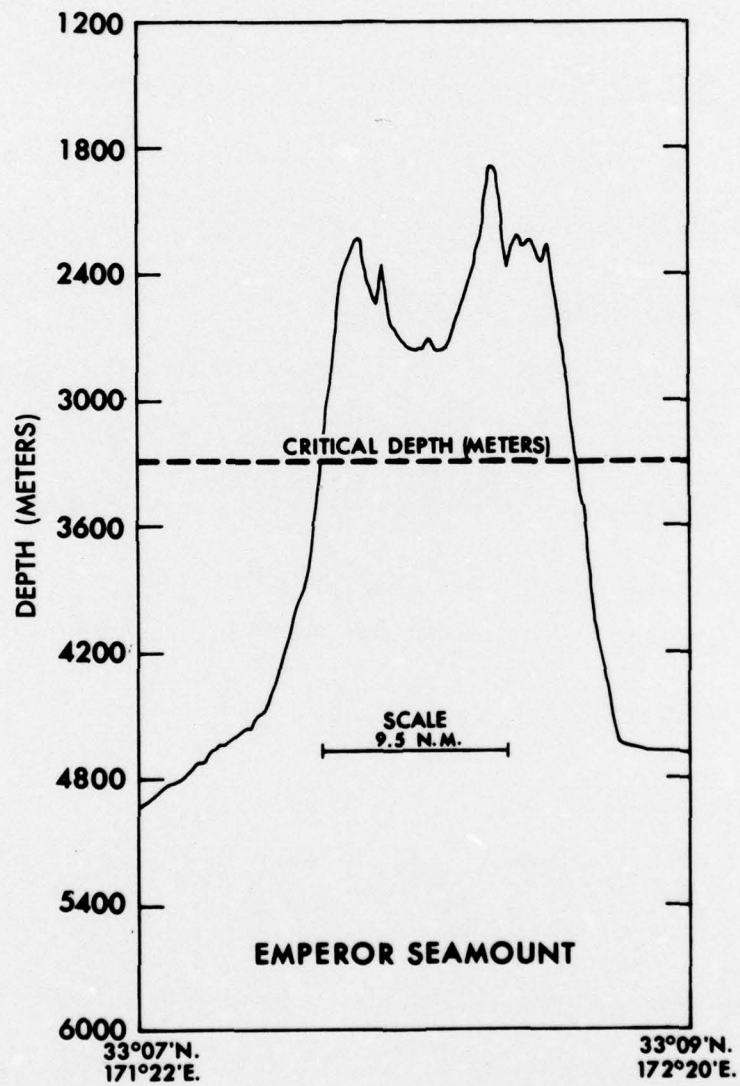


FIGURE 15 CRITICAL DEPTH ACROSS EMPEROR SEAMOUNT CHAIN

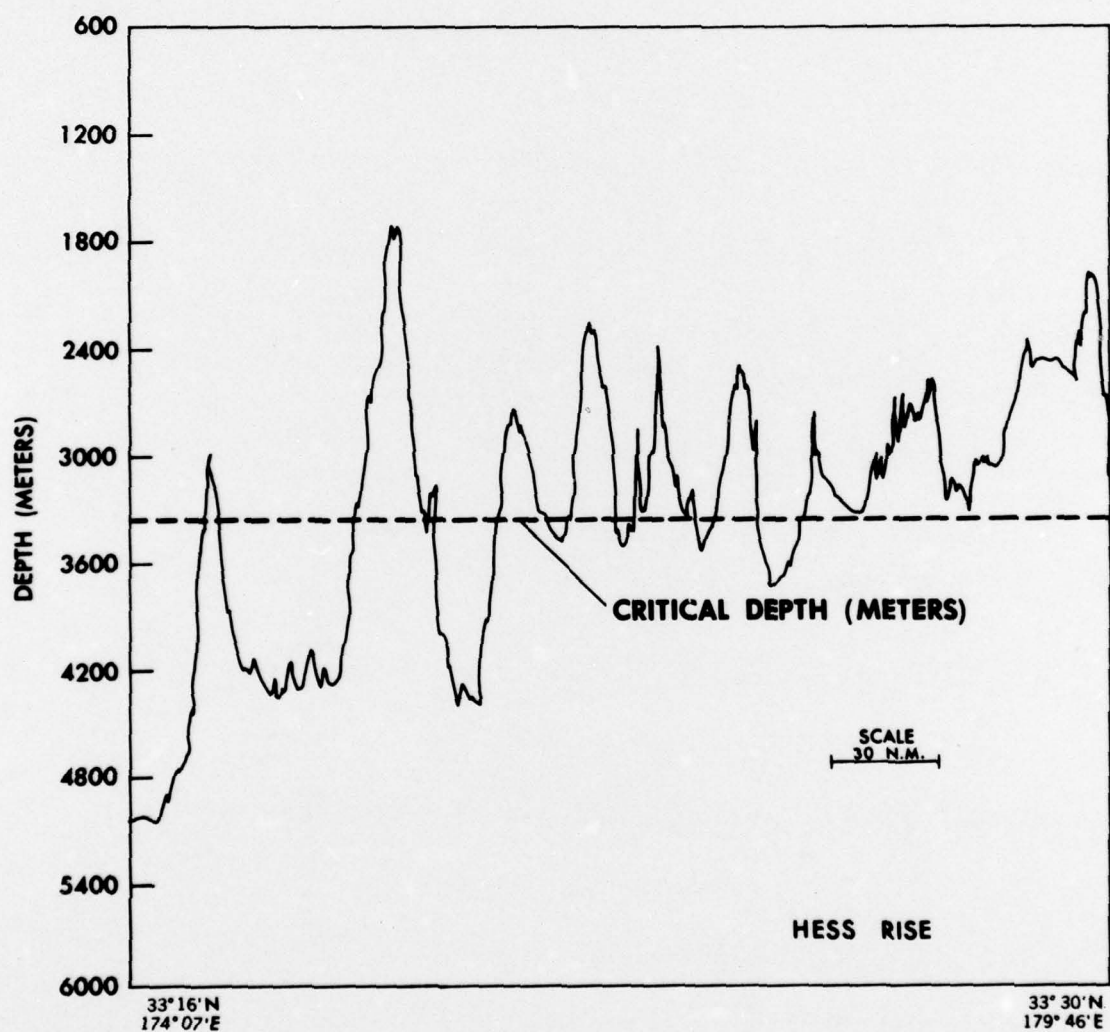


FIGURE 16 BATHYMETRIC SECTION ACROSS HESS RISE BETWEEN 33°16'N., 174°07'E AND 33°30'N., 179°46'E. SHOWING CRITICAL DEPTH.

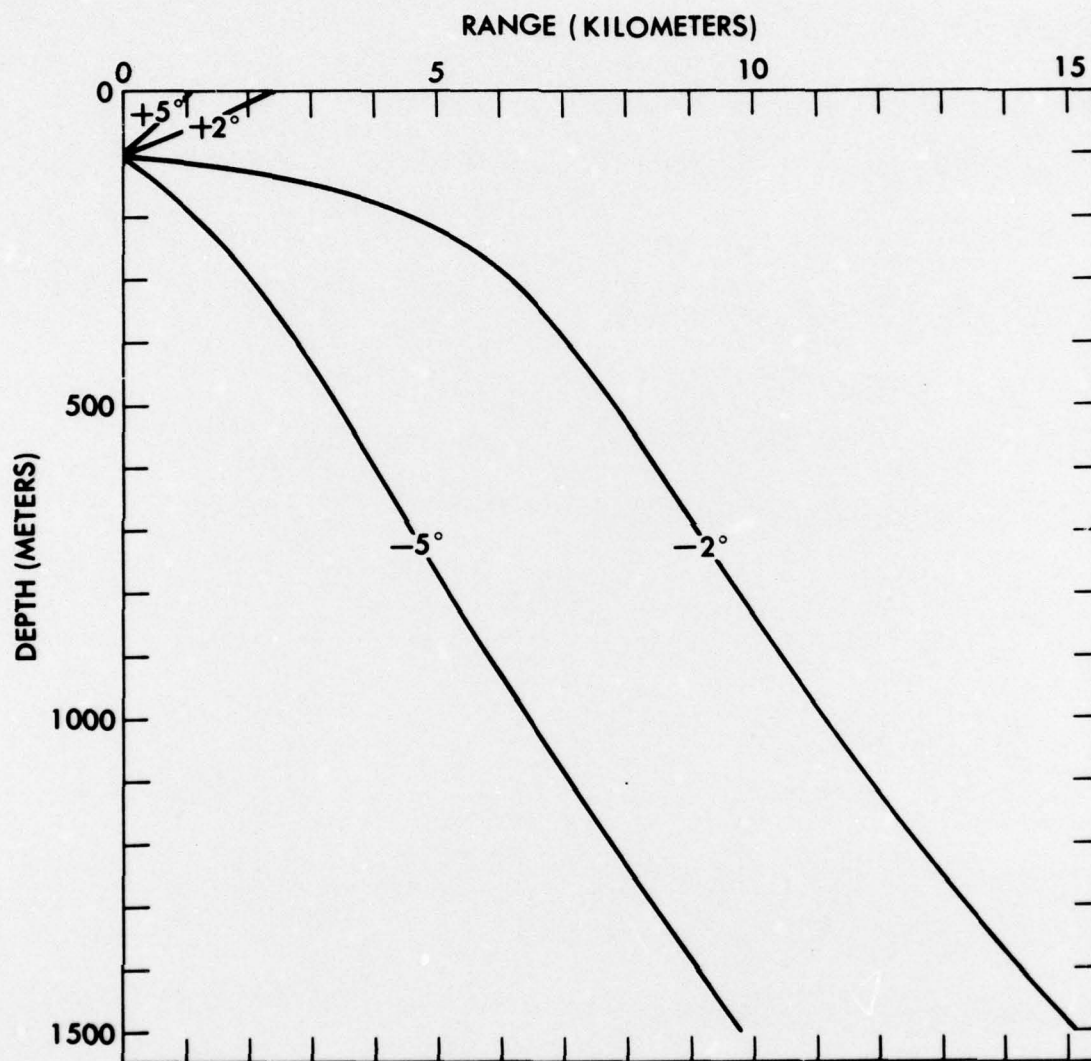


FIGURE 17 ACOUSTIC RAY PATHS STATION 2 16 APRIL 1976.

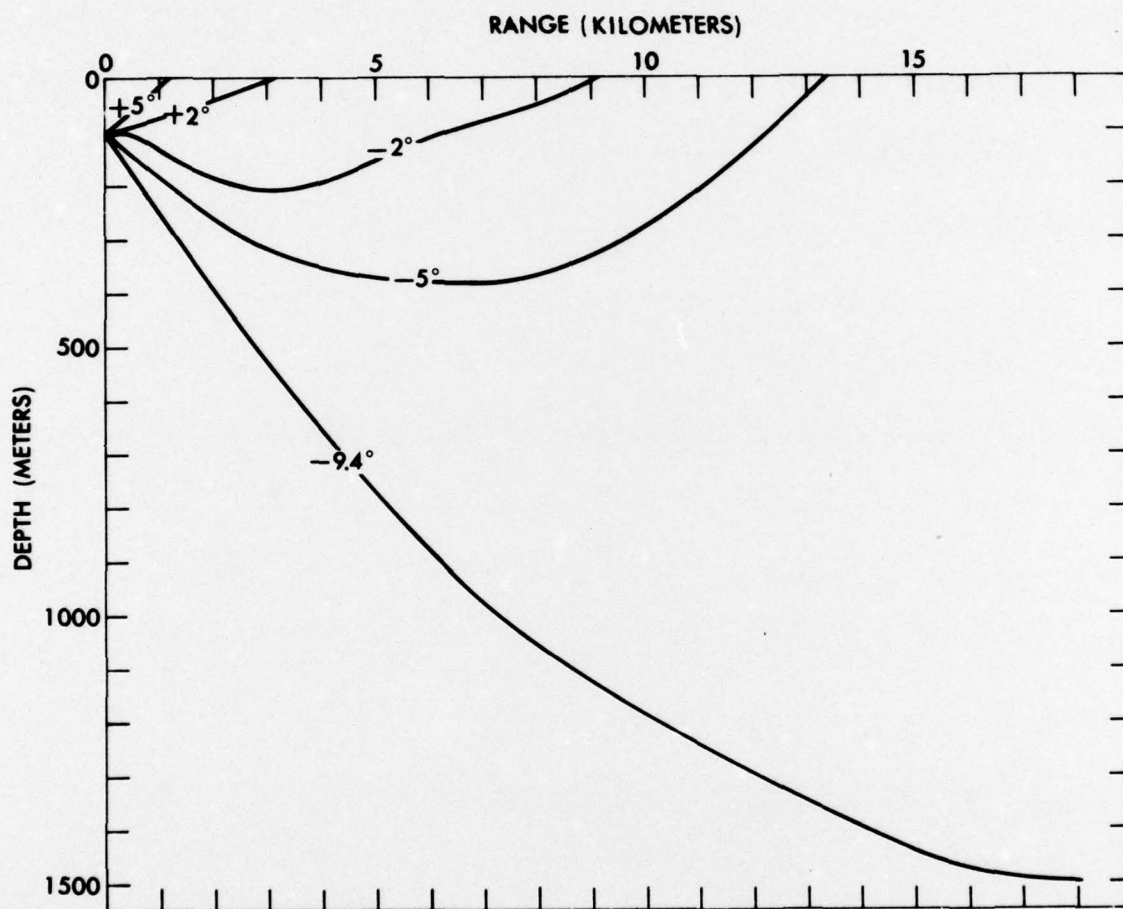


FIGURE 18 ACOUSTIC RAY PATHS STATION 3 16 APRIL 1976.

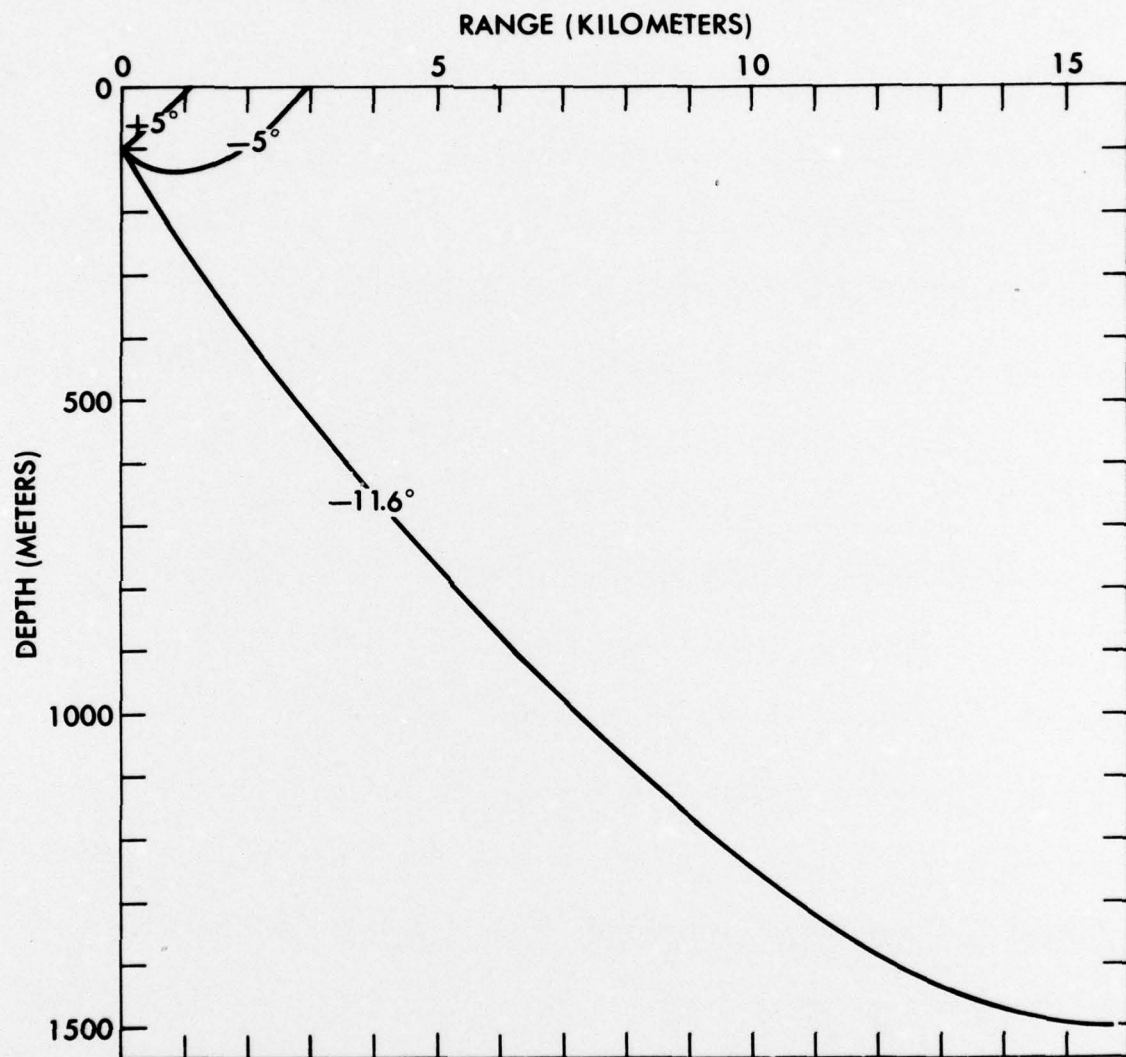


FIGURE 19 ACOUSTIC RAY PATHS STATION 8 19 APRIL 1976.

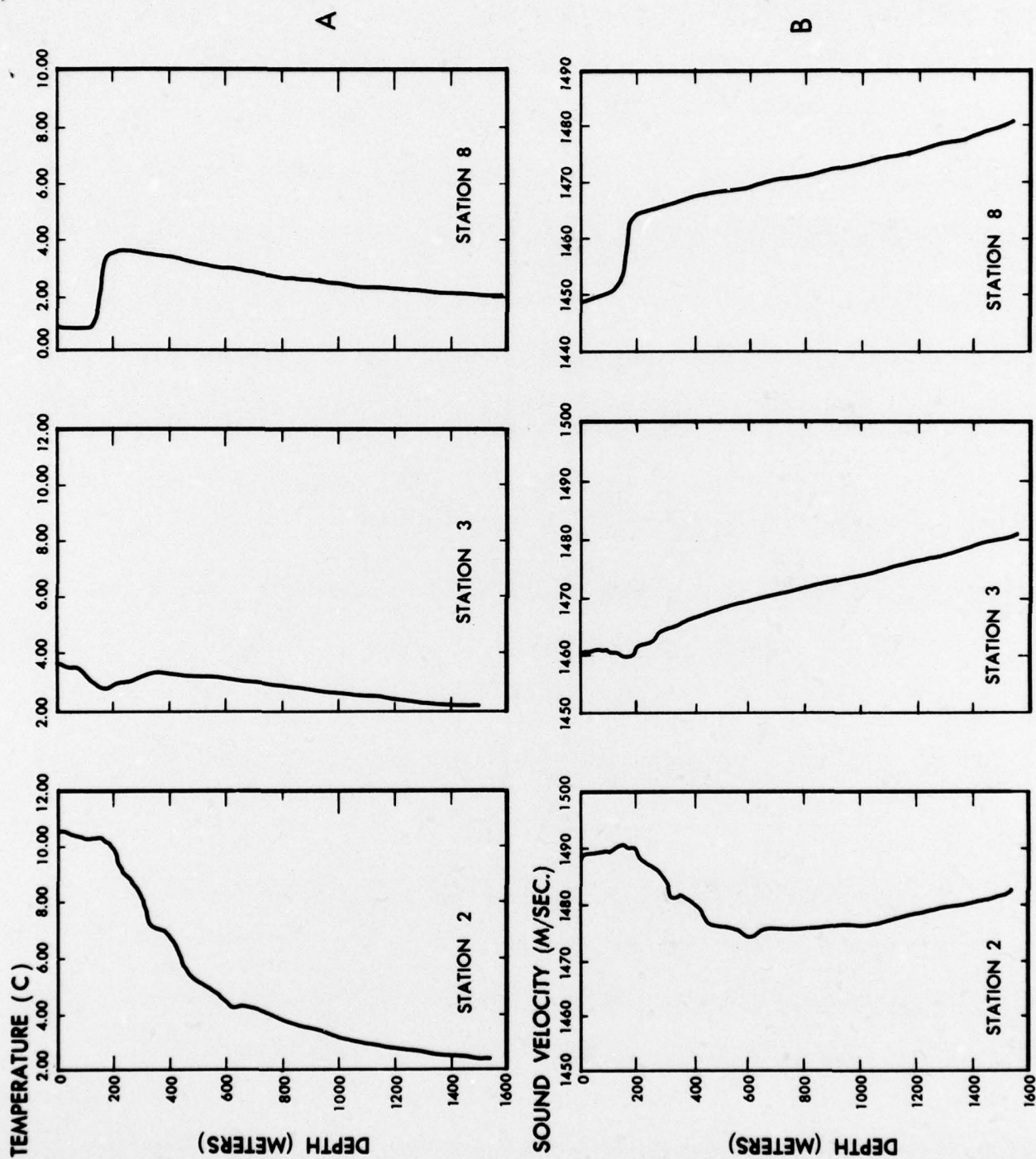


FIGURE 20 (A) TEMPERATURE AND (B) SOUND VELOCITY PROFILES AT STATIONS 2, 3 AND 8 APRIL 1976

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